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# Microwave Phase Shifters Using Ferroelectric (Ba,Sr)$TiO_3$ Films

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## ABSTRACT

The ferroelectric ($Ba_{0.6}Sr_{0.4}$)$TiO_3$ (BST) films were prepared on (001) MgO single crystals by pulsed laser deposition. Coplanar waveguide (CPW) type phase shifters controlled by external dc bias field were fabricated on BST films using a 2 μm thick metal layer to reduce metal loss. Microwave properties of the CPW phase shifter were measured using a HP 8510C vector network analyzer from 0.1 – 20 GHz. The fabricated CPW phase shifters (8 mm long) exhibited differential phase angle of 100 ° at 10 GHz with a dc bias field of less than 80 kV/cm between center and ground conductors. Furthermore, a stable differential phase angle (102 ± 3.5 °) was observed from another CPW while changing the power of incident microwave from –10 to +30 dBm. Gap size dependent dielectric constant of the BST film was observed and a simple correction method was suggested in the paper. These results demonstrate the possible application of ferroelectric tunable devices on a high power tunable wireless telecommunication.

## INTRODUCTION

Ferroelectric thin films with electric field dependent dielectric constant are being used to develop a new class of tunable microwave devices.[1-7] An important tunable microwave device using ferroelectric film is a wideband phase shifter which is the most important component of the phased array antenna. A simple co-planar waveguide (CPW) type phase shifter has advantages over other type phase shifters; easy fabrication with one-mask, easy to measure the microwave characteristics, and easy to extract film parameters.

In this paper, we report the microwave characteristics of the CPW fabricated on ($Ba_{0.6}Sr_{0.4}$)$TiO_3$ (BST) in terms of differential phase shift, and dielectric constant of BST. The fabricated CPW phase shifters exhibited a large differential phase angle with a dc bias field of less than 80 kV/cm between center and ground conductors. Furthermore, a stable differential phase angle was observed from another CPW while changing the power of incident microwave from –10 to +30 dBm.

At the end of this paper, we will discuss dielectric properties of the BST film in terms of the gap size of the device, which exhibits that the dielectric constant of the BST extracted by the conformal mapping increases with decreasing gap size. We introduced a simple empirical method to correct dielectric constant of a thin layer of high-k material.

## FILM GROWTH AND DEVICE FABRICATION

Single phase BST films were deposited using a well-known pulsed laser deposition (PLD) method onto (001) MgO single crystal. A focused Kr:F excimer pulsed laser was used to ablate BST target. MgO substrates were heated at 750 °C and the deposition chamber was kept in the oxygen pressure of 170 mTorr. The thickness of the BST films were controlled by changing the deposition time, and confirmed from a cross-sectional view of the film by scanning electron

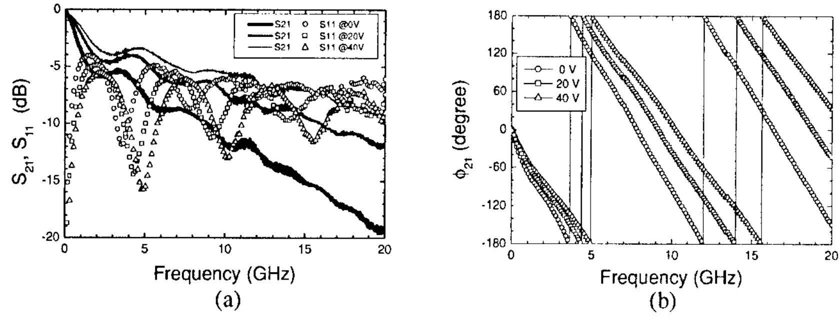


Figure 1. Frequency dependant measured microwave properties of CPW with changing bias voltage; (a) magnitudes of $S_{11}$ and $S_{21}$, and (b) phase of $S_{21}$.

microscopy. The structure of the films were routinely investigated by x-ray diffraction, and found be epitaxial film growths. A thick Au/Cr layer (2 μm) was deposited by sputtering method. Devices were fabricated on BST films through a conventional photo-lithography with a dry etching technique. Microwave properties of the CPW's were measured at 0.1 - 20 GHz range by a HP 8510C network analyzer. Dielectric constants of the films were extracted using a modified conformal-mapping method from measured S-parameters and dimensions of devices.

## A TYPICAL CPW PHASE SHIFTER

**Figure 1** shows a typical frequency dependent microwave property of the CPW with external bias voltages (0 - 40 V). Note that the maximum dc bias voltage was limited to 40 V to protect the network analyzer. The dimension of the corresponding CPW is 25 μm (width), 5 μm (gap), and 8 mm (length), and the thickness of the BST film is 3000 Å. From fig. 1. (a), the measured insertion loss $S_{21}$ decreases with increasing frequency, and improving with bias voltage, which is a typical trend of CPW type. Decreasing electrical length of device with increasing bias voltage is evident from the frequency dependant phases of $S_{21}$ shown in fig. 3 (b). The measured phase shift angle between 0 and 40 V ranges 100 – 177 ° at 10 – 20 GHz, respectively. These values are significant since large differential phase shifts are achieved with such a low bias voltage of 40 V. Since differential phase shift angle with 40 V is not saturated yet (fig. 3 (b)), it will increase further with a higher dc bias voltage and expected to reach at least 180 ° at 10 GHz with 100 V. Maximum of return loss ($S_{11}$) ranges from -4 ~ -7 dB, which

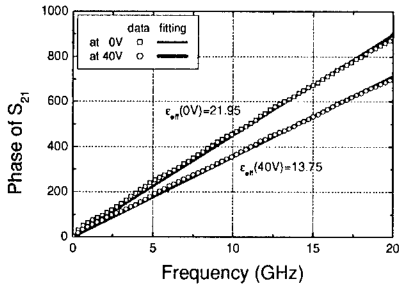


**Figure 2.** Total phase of $S_{21}$ and linear fitting to extract effective dielectric constant of CPW.

suggests that the impedance of the device is not matched to the probe impedance of 50 Ω. However, $S_{11}$ can be suppressed further using a matched design by controlling the dimension of the device. The measured insertion loss at 10 GHz ranges from –12 to –5.5 dB with 0 and 40 V, respectively, which mostly caused by a poor impedance matching, an electrode loss, and an unexpectedly lossy BST film (0.12 (at 0V) > tan δ > 0.03 (at 40V)).

Dielectric constant of the ferroelectric BST film is calculated from the total phase of $S_{21}$, which is equivalent with the electrical length. The electrical length of the device can be expressed as following,

$$\phi_{21} = 2 f_o \sqrt{\varepsilon_{eff}\mu_{eff}} \times l \times 180 / c \,, \quad \text{---------- (1)}$$

where $f_o$ is the operating frequency, $\varepsilon_{eff}$ and $\mu_{eff}$ are the effective dielectric constant and magnetic permearbility of the device, respectively, $l$ is the length of CPW, and $c$ is the light velocity in the air. Figure 2 shows that the measured total phase $\phi_{21}$ of the CPW agrees well with those of fitted using eq. (1) when $\mu_{eff} = 1$. Minor deviations at low and high frequency ends are observed in the graph, which may attributed to the frequency dependent non-linear response of ferroelectrics. To extract the dielectric constant of ferroelectric film, a modified conformal mapping technique has been used.[8,9] Dielectric constant of substrate, film, and air have the following relation,

$$\varepsilon_{eff} = k_{sub}\varepsilon_{sub} + k_{film}\varepsilon_{film} + k_{air}\varepsilon_{air}, \quad \text{---------(2)}$$

where $k$'s are corresponding to the filling factors for the substrate, film and air. The calculated film dielectric constant decreases from 510 at 0 V to 250 at 40 V. This is corresponding to 50 % of dielectric constant change with 80 kV/cm of a dc bias field, which is comparable with those of the reported BST films.[1-7]

Another CPW with 10 μm gap has been exposed to high power microwaves upto +28.3 dBm ( ~1 Watt) to test device reliability under high microwave powers.[10] The input microwave power were swept from – 10 to 28.3 dBm, which have been accomplished with appropriate sets of microwave power amplifiers and/or attenuators with power dividers to monitor the input and

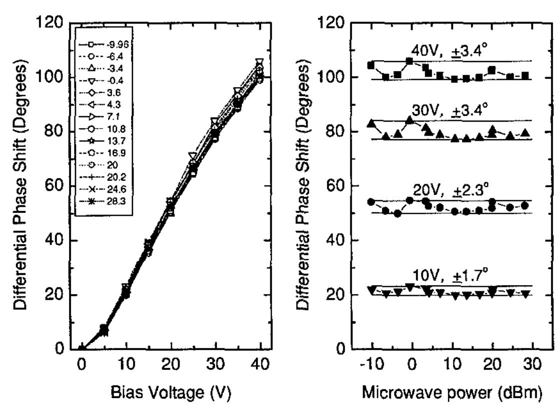


**Figure 3.** (a) Bias voltage dependent differential phase shift with varying microwave power from –10 to 28.3 dBm, and (b) stable differential phase angle with microwave power sweep.

output power of the device. Figure 3 exhibits stable differential phase shifts with less than 4% of deviations while changing microwave powers. Note that relatively large deviation can be attributed to minor fluctuations caused by changed microwave accessories on the path to change microwave power. A stable phase shift of 102 ± 3.5 ° were achieved with bias voltage of 40 V, while changing input microwave power from −10 to +28.3 dBm. This result clearly demonstrates that the high power stability of the ferroelectric devices.

## GAP DEPENDENT PROPERTIES OF PHASE SHIFTERS

It is difficult to extract a dielectric constant from a high dielectric thin layer. Though dielectric constants of BST films have been calculated using (modified) conformal mapping method, the validity of the model with extreme boundary conditions need further verifications with experimental results.

To investigate the dielectric constant of the films, microwave properties have been measured from devices with different gap sizes (20, 15, 10, 7, and 5 μm), while the width of the center conductor was kept in 20 μm and the length of the device was fixed at 3 mm. Thickness of the BST film used in this experiment is 630 nm measured by SEM. Figure 4 shows frequency dependent total phases of two CPW's with gap size of 5 and 20 μm. The effective dielectric constants of CPW's were extracted by using the eq. 1. Then, the dielectric constant of the BST film was calculated from the effective dielectric constant based on the conformal mapping method (eq.2), and the resulting dielectric constant of the film without bias field are shown in figure 5.

From the figure 5, one can find an interesting tendency that the calculated dielectric constant decreases with increasing gap size. The dimensions of the devices were investigated using SEM, and found to be 1 μm larger width and narrower gap than the original design. Though lower dielectric constants with measured device dimensions were extracted, dielectric constants still decrease with increasing gap size as shown in Fig. 5. This suggests that the conformal mapping and/or the nature of the ferroelectrics are not understood completely. Since we are dealing with high dielectric constant materials, the conformal mapping developed for low dielectric constant materials may cause some degree of deviation when the condition is extreme, such as high-k,

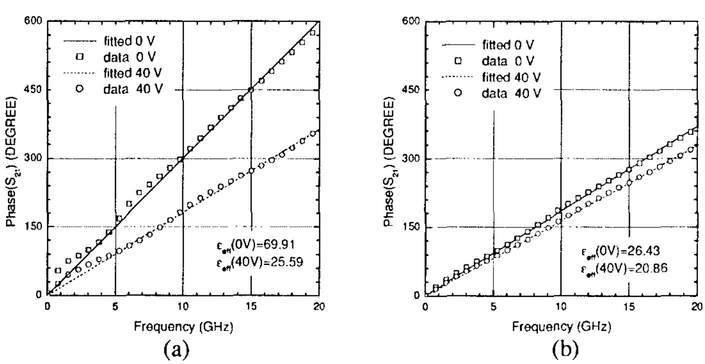


Figure 4. Total $S_{21}$ phase of the CPW's with 3 mm in length, 20 μm in width, and (a) 5 μm and (b) 20 μm of gap sizes.

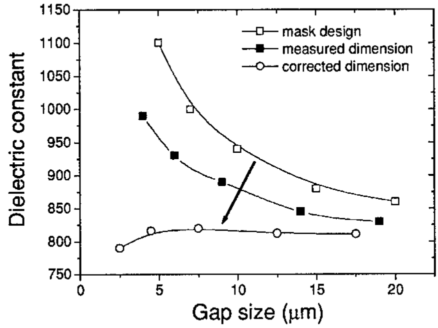


Figure 5. Gap dependent dielectric constant of the high dielectric BST film without bias fields.

thin-layer, and narrow gap, and etc. The other possible origin of deviation may come from the anisotropic dielectric constant of ferroelectric films hinted from the orientation dependent dielectric constants of tetragonal and distorted cubic ferroelectrics.[1, 11-13] This should investigated further to get clear picture in a future.

Assuming that the dielectric constant of the film without dc bias field is unique and independent from the gap dimension, and the modified conformal mapping is valid, a simple correction procedure has been developed to find a unique dielectric constant of the film without a complicate scheme.

An empirical method suggested in here is introducing a virtual device dimension: increased center width and decreased gap size from the measured ones to calculate dielectric constants using the same modified conformal mapping. Dielectric constants calculated with the virtual device dimensions (2.5 μm wider width and 2.5 μm narrower gap than those of design) are shown in Figure 5. Corrected dielectric constants are 810 with a small deviation (less than 2%), which is match well with EM simulation value of 750. More detailed discussion including EM simulation results will be published in elsewhere.

## SUMMARY

CPW type phase shifters have been fabricated on BST/MgO using a 2 μm thick metal layer. Microwave properties of the CPW's presented in here have been summarized in Table 1. The fabricated CPW phase shifter (25um (width), 5um (gap), and 8mm (length)) exhibited differential phase angle of 100 – 177 ° at 10 - 20 GHz with a dc bias field of 80 kV/cm between

Table 1. Summary of microwave properties from the CPW devices reported in this paper.

| | Dimension ($g$, $w$, $l$) | Film thickness | $\Delta\phi_{21}$ (10,20GHz) | $\varepsilon_{BST}$ (0, 40V) | $S_{21}$ (0, 40V) @10 GHz | $S_{11}$ (0, 40V) @10 GHz |
|---|---|---|---|---|---|---|
| CPW I | 5μm, 25μm, 8mm | 3000Å | 100, 177 | 510, 250 | -12, -5.5 | -6, -12 |
| CPW II | 10μm,10μm, 10mm | 3200Å | 102, 191 | --- | -13, -8 | -18, -19 |
| CPW III | 5μm, 20μm, 3mm | 6300Å | 119, 223 | 790, 245 | -10, -3 | -3, -10 |
| CPW IV | 20μm,20μm, 3mm | 6300Å | 23, 40 | 811, 590 | -2.8, -1.4 | -11, -18 |

center and ground conductors. Furthermore, a stable differential phase angle (102 ± 3.5 °) has been observed although the power of incident microwave was swept from −10 to +30 dBm. Gap size dependent dielectric constant of the BST film was observed, and a simple correction method was suggested by adjusting width and gap of devices. The corrected dielectric constant of the BST film was found to be 810 ± 5.

In this paper we clearly demonstrated that possible application of ferroelectric tunable devices on a high power wireless telecommunication.


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